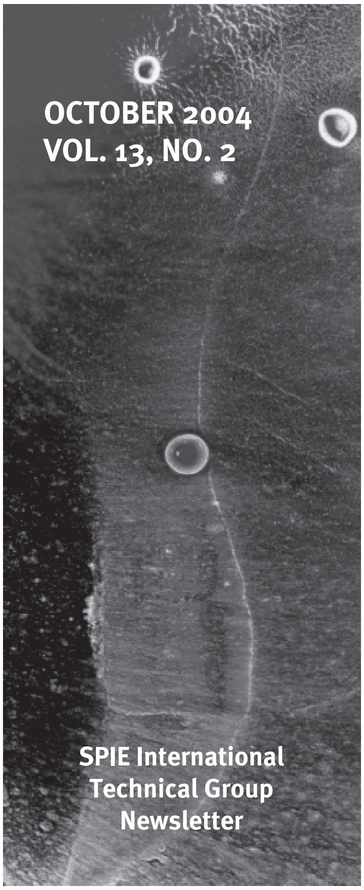
The International Society
for Optical Engineering



OCTOBER 2004
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SPIE International
Technical Group
Newsletter

# ROBOTICS AND MACHINE PERCEPTION

## Biorobotic study of Norway rats in individuals and groups

Norway rat pups provide an excellent system for the biorobotic study of embodied, environmentally-embedded, sensorimotor-based intelligence. They are sufficiently simple, have a protracted developmental period, and exhibit interesting behavior at both individual and group levels. As altricial mammals, Norway rat pups have underdeveloped senses and poorly-coordinated sensorimotor systems. They are born deaf and blind, remaining so for the first two weeks of life, and have very limited use of olfactory cues, relying primarily on tactile sensors.

Individually, rat pups embody a host of taxes, or environmental orientations. The most salient of these is thigmotaxis, an orientation toward objects, which causes rat pups to follow walls, 'snoop' in corners, and aggregate in huddles with other pups. Rat pups also exhibit a negative phototaxis, locomoting away from light sources visible behind their eyelids. This taxis is observed for a period prior to the opening of their eyes. Rat pups' extended sensory development allows us to sequentially implement touch sensors, primitive light sensors, and full-blown visual sensors, building the corresponding control systems step-by-step.

Although pups aggregate into groups from birth, data modeling has shown that seven-day-old pup activity is independent of other pups, while ten-day-old pups' behaviors are coupled.[1] One question, then, is what gives rise to these inter-pup dependencies. We are currently entertaining two hy-

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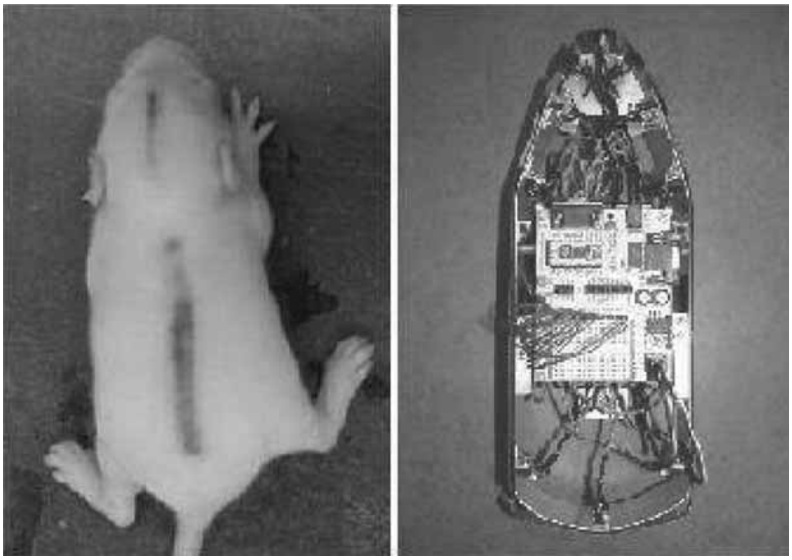

*Figure 1. Comparison of rat and robot highlighting similar morphology.*

***Calendar**—See page 10*

***Technical Group Registration Form**—See page 11*

### NEWSLETTER NOW AVAILABLE ON-LINE

Technical Group members are being offered the option of receiving the Robotics and Machine Perception Newsletter electronically. An e-mail is being sent to all group members with advice of the web location for this issue, and asking members to choose between the electronic and printed version for future issues. If you are a member and have not yet received this message, then SPIE does not have your correct e-mail address.

To receive future issues electronically, please send your e-mail address to: `spie-membership@spie.org` with the word `Robotics` in the subject line of the message and the words `electronic version` in the body of the message.

If you prefer to receive the newsletter in the printed format, but want to send your correct e-mail address for our database, include the words `print version preferred` in the body of your message.

## Editorial

# Welcome to this, the second issue of the R&MP newsletter for 2004.

The articles in this issue cover a range of topics and applications in robotics and machine perception. Learning, for example, is a continuing theme in robotics and artificial intelligence. It is represented here in the article by Santos, who describes efforts aimed at formulating theories relating utterances to perceptual (visual) observations. The overall goal is to build machines capable of learning tasks by observation of humans.

Cooperation is another continuing theme in robotics. It is represented here in the articles by Bouloubasis et al. and May et al.. The two articles offer contrasting themes in cooperative robotics; the first takes an engineering perspective, focusing on designing robot systems for cooperation, whereas the second takes a more science-oriented perspective, focusing on mimicking cooperative behaviour observed in rats. Both draw strongly on sets of low-level behaviours to formulate models of cooperation. Bouloubasis et al. also emphasise the concept of modularity as a basis for systems design and reconfigurability, and its realisation in the emerging area of networked robotics.

Human-robot interaction is a third theme in this issue, represented in the articles by De Gersem et al., Carignan et al., and McElligott et al..

The first two focus on very different applications in medicine. De Gersem et al describe methods for enhancing haptic feedback in order to afford the discrimination of tissues based on stiffness. Carignan et al., on the other hand, describe methods for assessing the physical condition of a patient and for performing rehabilitation tasks remotely. Both applications offer clear benefits to the doctor and to the patient. The interaction in both cases is also via the Interent, which is also the medium for the online robot arena described by McElligott et al.. In the latter case, however, the focus is on education and invoking the participation of school children and general members of the public, whereas the first two articles focus on the experienced professional.

There are many issues that cross these different articles and underpin important research areas in robotics and machine perception. We encourage you to read the articles and pursue the references for further details.

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## Contributing to the Robotics and Machine Perception Newsletter

***News, events, and articles***

If there are things you'd like to see us cover in the newsletter, please let our Technical Editor, Sunny Bains {sunny@spie.org}, know by the deadline indicated on the right. Before submitting an article, please check out our full submission guidelines at:

`http://www.sunnybains.com/newslet.html`

***Special issues***

Proposals for topical issues are welcomed and should include:

- A brief summary of the proposed topic;
- The reason why it is of current interest;
- A brief resumé of the proposed guest editor.

Special issue proposals should be submitted (by the deadline) to Sunny Bains and will be reviewed by the Technical Group Chair.

### *Upcoming deadlines*

***24 November 2004:*** *Special issue proposals.*

***10 December 2004:*** *Ideas for articles you'd like to write (or read).*

***4 March 2004:*** *Calendar items for the 12 months starting April 2005.*

# Robotic rehabilitation over the internet

Figure 1. A researcher engages in a game of air hockey on an InMotion2 robot.

Robots have been explored as possible rehabilitation aids in laboratory settings for well over a decade. These investigations have recently expanded into the field of 'teletherapy' whereby a clinician can interact with patients in remote locations. However, time-delays encountered in force feedback between remotely-located rehabilitation devices can cause instability in the system, and have so far prevented widespread application over the internet.

The ISIS Center at Georgetown University Medical Center has recently assembled a robot rehabilitation testbed consisting of a pair of InMotion2 robots[1] connected over the internet (see Figure 1). The specific aims of our research are twofold: to enable a clinician to assess the physical condition of a patient's arm using metrics such as strength, dexterity, range of motion, and spasticity; and to help a clinician perform co-operative rehabilitative tasks with a patient using a virtual environment intended to simulate active daily living (ADL) tasks.

An example of a cooperative rehabilitation task is depicted in Figure 2. The patient and therapist 'pick up' opposite ends of a virtual beam by grasping the handle at the end of the robot or 'master' arm.[2] The mass parameters of the object such as mass, length, and inertia can be adjusted to correspond to real-life objects using a graphical user interface (GUI) on the robot's computer. As the object is being 'lifted', the side that is lower will begin to feel more of the weight, thus stimulating the participants to maintain the beam in a horizontal position. Also, if one side tugs on the object, the other side feels, it thus encouraging a co-operative strategy to lift.

Time-delay compensation is key to avoiding instabilities in force-feedback interaction over a distance. In our research, the wave-variable method emerged as the most natural approach for manipulating virtual objects over the internet.[3] Instead of sending force commands directly, an impedance 'wave' command is issued by the master and then subsequently reflected by the virtual object or 'slave'. How much of the wave is reflected depends upon the impedance of the virtual object: a compliant object will not reflect the incoming wave as greatly as a rigid wall.

The robots are controlled by computers running RT-Linux and connected to the internet as illustrated in Figure 3. When controlling a patient's robot directly, a client application on that patient's computer connects to a server on their therapist's computer. User Datagram Protocol (UDP) enabled communication speeds of up to 100 16-byte datasets per second. A virtual object generator (VOG) calculates the motion of the object resulting from the force inputs from the patient and the therapist.[4] An artificial time delay ($T^1$ in Figure 3) is introduced between the VOG process and the local controller to maintain symmetry in communication between the VOG and the two robots.

To date, we have successfully conducted the virtual beam task between Georgetown University and Interactive Motion Technology in Cambridge, Massachusetts. Internet delays of up to 110ms were observed which caused borderline stability without compensation. The wave-variable controller was found to be robust to variations in time delay, and performance degraded only gradually with increasing delay. The degradation manifests itself as a higher perceived inertia at the handle which was still quite manageable even with artificially-induced delays of over 1s.

We are currently testing even larger time delays and examining the incorporation of sensed force into the wave-variable methodology to produce higher-bandwidth feedback to the clinician. In addition, a head-mounted display and tracker are being integrated into the system to allow for more realistic simulations using three-dimensional visualization. Coordination of the haptic and visual feedback in the simulator is an area of ongoing research.

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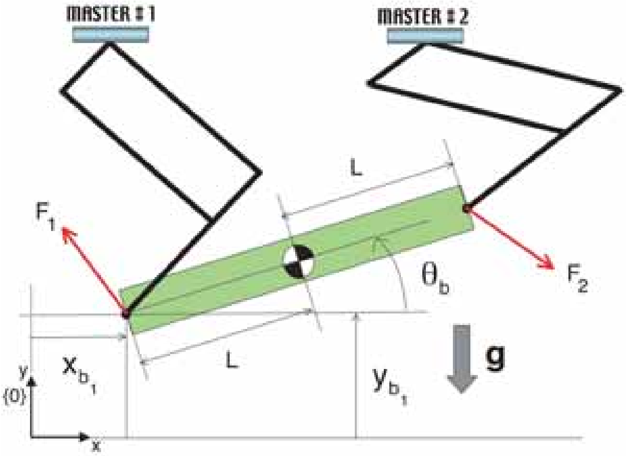

Figure 2. A virtual beam task realized with two robot handles coincident with the ends of the beam.

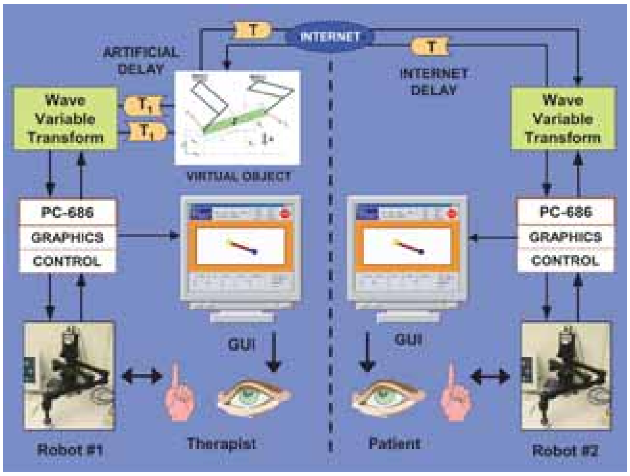

Figure 3. System architecture for implementing a cooperative internet task.

# Systems design for working rovers

A current theme in the exploration of Mars using robotics systems is the construction of habitats for maintaining a robotic and eventual human presence.[1] A key aspect of this task is the transport of extended payloads using a set of cooperating robots. The work presented in this article is part of ongoing research in the Active Robotics Laboratory (ARL) at the University of Reading to explore networked robotics concepts for the coordination and control of multi-robot systems[1,2] for such tasks.

The networked robotics approach assumes the presence of a set of resources distributed across the robot platforms. These resources can be recruited in different architectural configurations to create, across the platforms, a set of networked robotics agents. A single robotic agent may draw from a number of physically-decoupled robot platforms. This provides the possibility of configuring the multiple robot systems into a single robotic entity when close inter-robot coupling and coordination is required. For example, the dual-robot transportation task incorporates requirements for various levels of coupling and coordination:[3] the approach to the pick-up point can be relatively autonomous whereas grasping requires coordination and traversal requires both coupling and coordination.

The design of the ARL Rovers shown in Figure 1 has been customized to integrate the requirements for the complete task and hence has a number of constraints it needs to satisfy. It is strongly influenced by the traversal constraints, specifically the requirement to traverse over uneven terrain, as well as by the fact that the rovers trajectory cannot be perfect. As a result, the load has six degrees of freedom (DOF) with respect to the grippers. The manipulator systems and the two mobile bases must be able to accommodate this 'deflection' and also achieve the desired motion.

At present, only two agents have been constructed. Each comprises a mobile base, a manipulator, and a stereo camera system. The low-level controller is built around the PIC16F873 microcontroller and the on-board high-level controller will be a MINI-ITX board equipped with a wireless modem. The mechanical design of the rovers incorporates a rocker-bogie mobility system with a passive suspension mechanism. The motorized six-wheeled drive uses its two rear wheels—via servomechanisms—for steering. The manipulators consist of three major components: a two-DOF arm, a passive but compliant one-DOF wrist, and an active gripper mechanism (see Figure 2). Apart from the motors and the gearboxes, all the components were handcrafted.

*Figure 1. The Active Robotics Laboratory rovers.*

There are a total of 17 sensor signals available on each unit, giving information about the status of the load (i.e. the amount of slide of the load within the gripper mechanism as well as the angle of the load with respect to the rover body), the position of the joints and the wrist, the stress imposed upon the fingers by the load, the relative motion of the base, and the relative position of each of the rovers with respect to each other. Many of the switches had to be custom made in order to fit the application.

The information obtained from the sensory systems is fed to a small network of three microcontrollers. A design goal is modularity, so if there are cases where certain sensory information is needed by, say, two controllers, they are both connected to the particular sensor. Each of the modules runs almost independently and there is minimum communication between them. This facilitates the addition of modules. The communication between the modules is accomplished through a serial interface with the high-level controller acting as a bridge. The controllers will use the sensory signals to not only perform the basic control but also to form behaviors and respond in the way that each situation demands. A number of reflexive behaviors have been developed to support the dual transportation task. For instance the Grasp Behavior (GB), once enabled, will automatically open the fingers if excessive stress is detected. The behaviors can suppress basic control functions: for example if the command 'close gripper' is given whilst the GB is enabled, and if the fingers open because there is excessive stress in the gripper, the fingers will continue to open until the stress levels become acceptable or the behavior is disabled.

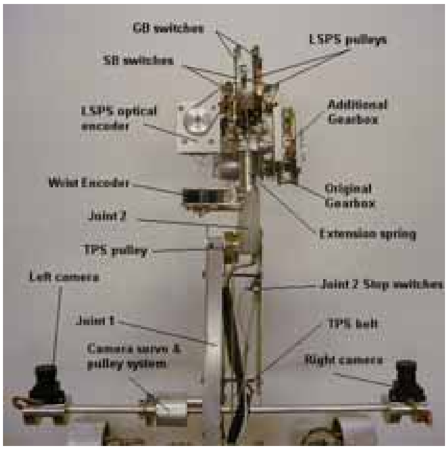

*Figure 2. The rover manipulator.*

First in the hierarchy of the low-level controller are 'sequences' and each sequence is divided into 'states'. Once it is in a particular sequence, the robot will execute actions in series in order to achieve a goal. An example is the approach sequence in which the rover will approach and align itself with the load. When the approach sequence is initiated, each of the modules will enter its own version of that sequence. During the approach, the modules will collectively use the information obtained by the sensors to judge whether a particular state in their respective sequence has been reached and, if so, to move to the next state until the approach sequence is completed. In some cases behaviors will be utilized by a sequence. There is minimal communication between the modules and no guidance from the high-level controller. The system is set up in a way such that each module will recognize its current state and act accordingly.

The low-level controller has been tested successfully and the next stage of the work is to integrate the sequences under the guidance of the high-level controller. This stage will include the introduction of visual guidance for the task.

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# Looking for logic in perceptual observations

In his seminal work[1] Bertrand Russell suggests that the *discovery* of what is really given in perceptual data is a process full of difficulty. We have taken this issue seriously in AI by applying a knowledge discovery tool to build theories from perceptual observation. In particular, this article introduces some of the research we are conducting on autonomous-learning rules of behavior from audio-visual observation.

In our framework, classification models of perceptual objects are learned (in an unsupervised way) using statistical methods that enable a symbolic description of observed scenes to be created. Sequences of such descriptions are fed into an off-the-shelf inductive logic programming (ILP) system, called Progol,[2] whose task is, in this context, to construct theories about the perceptual observations. The theories thus constructed are further used by an automatic agent to interpret its environment and to act according to the protocols learned.

In its current implementation, our system is capable of learning the rules of simple table-top games (and how to use them) from the observation of people engaged in playing them. Our basic motivating hypothesis for assuming game-playing scenarios is that these can provide both rich domains—allowing multiple concepts to be learned—and domains with gradually-increasing complexity, so that concepts can be learned incrementally. Moreover, it has been largely argued that games provide interesting ways of modelling any social interaction.[3]

The experimental setting used in this research is composed of two video cameras, one observing a table-top where a game is taking place, and another pointed at one of the players. This player will also have a microphone recording utterances that he produces when playing the game. The purpose of the second camera is to capture the facial movements of the player, whose voice is being recorded, so that a synthetic agent can reproduce them in similar situations. A schematic of the system is shown in Figure 1.

The vision system consists of a spatio-temporal attention mechanism and an object classifier. Classes obtained from vision data are used to provide a symbolic description of states of the objects observed on the table top. This is used as input data for Progol.

In particular, our interests in this research are twofold. The first aim of this project was the autonomous learning of perceptual categories from continuous data, grounding them into meaningful (symbolic) theories. The second (but no less important) aim is the autonomous discovery of simple mathematical rules from the perceptual observation of games. We shall consider these goals in turn.

### *Grounding symbols to the world*

In the current guise of this project, symbolic data provided by the audio and vision systems are input to the knowledge discovery engine as atomic formulae. Within these formulae, symbols for utterances are arguments of predicates representing *actions* in the world whereas symbols for visual objects compose atomic statements representing the *state* of the world. Both statements are time-stamped with the time point relative to when they were recorded. A relation *successor* connects two subsequent time-points. The task here is to use Progol to *discover* the relationship between the utterances produced by one of the players, and the objects played on the table. Therefore, we are interested in the autonomous learning of the connection of audio and visual objects within a particular context.

Some preliminary results of this research, presented in Reference 3, show that the system could learn accurate descriptions of simple table-top games.

### *Learning simple axioms from observation*

We next submitted the system to the challenge of finding the transitivity, reflexivity, and symmetry axioms from the observation of games without assuming any preconceived notion of number or any pseudo definition of ordering. This research is described in References 5 and 6, where these axioms are obtained from noisy data with the help of a new ensemble algorithm that combines the results of multiple Progol processes by means of a ranking method.

It is worth pointing out that the discovery of simple mathematical axioms from observation, without assuming any explicit background knowledge, was not set for pure intellectual pleasure. In fact, I believe that the capacity of abstracting general truth from simple data is essential if any system is to solve new problems and to overcome obstacles not seen before.

### *Conclusion*

The final aim of the project summarized above is to build a machine capable of learning (and further executing) human tasks by observing people accomplishing them. The preliminary results of this research suggest that the combination of statistical methods with inductive logic programming applied to the task of learning behavior by observation is a promising route towards our final goal.

*Chris Needham, Derek Magee, Anthony Cohn, and David Hogg are all active participants in the development of the project described above. Thanks to Brandon Bennett and Aphrodite Galata for discussions and suggestions.*

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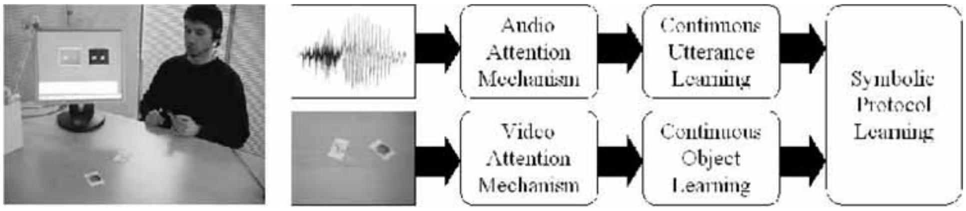

*Figure 1. A schematic of the experimental set-up that allows machine-learning of game rules through observation.*

# A Mars Station online robot arena

An online robot system offers visitors to a website the opportunity to control a real robot that is normally located in a university laboratory, perhaps set up as part of a student project. A video stream delivered to the user's browser is normally the means by which the user can watch what is happening in the remote environment. Over recent years, online robot systems have both moved out of the laboratory, into museums for example, or they have remained in the laboratory but encapsulated within specially-constructed arenas. It is also now possible to distinguish two types of online robot system: open systems that are primarily for public consumption, and closed systems that are used for recurring educational instruction. Open systems are particularly challenging since the designers often want to encourage continuing and repeated participation on the part of visitors. These systems may also have an educational value, seeking the public understanding of science.

Figure 1. Students learning about the design of the University of Reading Mars Station arena during the launch of the UK Mars Stations Network.

Figure 2. The painted surrounds add depth to the arena landscape.

A notable case in point is the ongoing USA and European missions to Mars.[1,2] What better use of an online robot system than to give the general public some sense of the wonder and awe that the professional scientists participating on these missions are experiencing? This has been the goal of The Planetary Society Mars Station concept, comprising a robotic rover that school children and general members of the public can drive about an arena that models a location on the surface of Mars.[3] We recently built such an arena in the Active Robotics Laboratory at the University of Reading as part of a project to set up a number of Mars Stations in the UK. The project was funded by the UK's Particle Physics and Astronomy Research Council (PPARC) under its Public Understanding of Science Small Awards Scheme. This article describes the construction of the arena and some novel techniques we used to maintain a tether to the rover as it moved about the terrain. The construction is in one sense simple, but nevertheless very effective in creating a visually-appealing terrain for visitors to explore.

The Mars Station arena, or 'diorama', models a specific geographic location on Mars. We chose to model the Mars location known as 'Eos Chaos'. This is a 'chaotic' terrain, meaning that it comprises a rugged unstructured landscape with steep escarpments and gullies. The basic frame for the arena was constructed from the metal under frames of two laboratory benches that were put together sideways: the top surfaces were lifted away, and the adjacent upper-longitudinal sections of the two benches were then removed to create a rectangular bay for the terrain. The bay structure is clearly illustrated in Figure 1.

The actual Mars terrain was constructed on a removable wooden base to allow easy maintenance and the option of swapping in alternative terrain models. Sections of wire mesh were bent into shape and pinned to the base to create the undulations used to reflect the chaotic terrain of Eos Chaos. The wire mesh surface thus created was then covered with about five layers of paper mache and painted with four layers of thick 'rustic red' house paint. Sand was added prior to the final coat in order to generate a more realistic surface. Rocks were later added to the landscape. The walls of the arena were made out of 3mm plywood and were painted by an art student with a Martian backdrop in order to provide a horizon and an impression of depth (Figure 2).

Figure 3. The hoist mechanism allows the tether to track the rover.

One of the main problems when setting up an online robot arena is supplying power to the robot so that it can be permanently live. A wire tether is normally used for mobile robots. The presence of the tether, however, creates an interesting challenge; specifically how to make sure that the rover can traverse the entire arena without getting tangled up. A cable running from a point well above the arena normally suffices, however our arena used an alternative method based on a simple passive-control mechanism. The tether is mounted from a hoist that can move in the X-Y plane above the arena. It passes through a simple ball mechanism that rests on a set of four switches. These are arranged such as to control two dc motors that drive the hoist in the X-Y plane. Figure 3 shows the hoist mechanism in profile. Whenever the rover movement causes one or more of the switches to close, the hoist moves to maintain a position approximately above it. Additional stop switches mounted to the arena frame prevent the hoist hitting either end of the arena. An additional weight, specifically a spare battery pack, was mounted on the LEGO rovers (designed and constructed by co-author Ashley Green) in order to compensate for the weight of the tether. Full construction plans for this rover design are available online.[4]

The University of Reading Mars Station was the focal point for the launch of the UK Mars Station network during the UK's National Science Week. Since its launch, the arena has required only minor maintenance and receives a regular stream of visitors each week.[5]

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## *Biorobotic study of Norway rats in individuals and groups*

*Continued from cover.*

potheses: that they are a function of differential sensorimotor integration abilities, or that they are rooted in the thermoregulatory benefits provided by huddling. We believe that these dependencies mark the emergence of social behavior, which is further developed later in life. Thus, Norway rat pups may also provide important insights into group robotics.

Robots were designed to capture the essential properties of the rat pups: they are long, with a somewhat-pointed head that rounds out at the nose, and have the same length to width ratio as rat pups (approximately 3:1), where the head constitutes 1/3 of the length. An aluminum skirt with 14 micro/limit (touch) switches epoxied to brass strips allows for a 360° sensory range. Sensor cluster density is substantially higher at the nose, mimicking a rat's sensory montage. Since rat pups' front legs are underdeveloped and aid only in steering, they primarily use their back legs for locomotion. Accordingly, the robots are equipped using rear-driven wheels with differential drive on a single chassis. Four identical robots have been completed to date, and four more are under construction. Currently, a subsequent generation is in the planning stages, which would have more sophisticated touch sensors, thermal detectors, and more mechanical degrees of freedom.

We are currently developing three classes of control system, with a number of variants of each. All attempt to derive the scope of behaviors above using sensorimotor contingencies alone. The first class is a reactive architecture that employs condition-action rules linking each sensor to a particular movement. The angle of movement is roughly commensurate with the sensor's angle to the prime meridian, thereby encouraging thigmotaxis. Multiple sensor activations are handled differently in separate architectures, including behavioral averaging, priority queuing, and random selection. These separate routines provide for comparisons of sensorimotor integration strategies. In the absence of an active sensor, the robot randomly chooses an action from its behavioral repertoire. This turns out to have a tremendous advantage over the standard approach, where some default movement is selected.

A second class comprises a suite of probabilistic architectures. These are much like the reactive ones, with the exception that each sensor is more weakly tied to its associated action. That is, a given sensor activation will trigger a given behavior with some probability less than one, where the remaining probability is dynamically allocated to the rest of the behavioral options. This routine takes a step toward decoupling artificially-imposed action selection, and yields striking pup-like behavior.

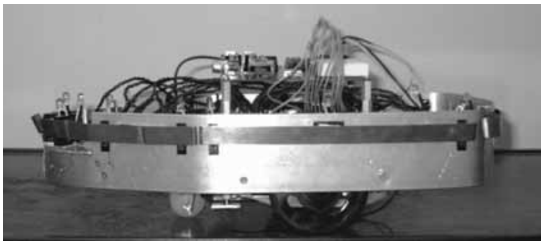

*Figure 2. Lateral view of robot.*

*Figure 3. Similar configurations of rats and probabilistically-controlled robots.*

Finally, a third class consists of a set of neural-network architectures. As an initial step, we've developed a two-layer, fully-distributed neural network employing a reinforcement learning algorithm. The input layer represents the 14 sensors, and the output layer the entire behavioral repertoire. The learning algorithm adjusts input-output weightings based on time between sensor contacts, again encouraging thigmotaxis. With these architectures, action selection is left wholly unspecified, and sensorimotor contingencies develop over time, rather than being predetermined. We anticipate that all of the above architectures will yield novel results and provoke interesting new ideas, making important contributions to robotics and biology alike. For more information on our study, please refer to Reference 2 and 3.

*This work is supported by the United States National Science Foundation under Grant Number ITR-0218927.*

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## Enhanced haptic sensitivity in surgical telemanipulation

*Continued from page 12.*

implementation of enhanced sensitivity in the desired stiffness range.

Figure 2 shows some experimental results, where an elastic rubber band was stretched using a one-dimensional teleoperation system. The position-force curve shows a changing slope, corresponding to a changing local stiffness. Thereby, two major areas can be assigned. At first, when the band is only slightly stretched, a stiffness of about 220N/m is detected. Further stretched, the stiffness drops to about 170N/m. The haptic device used shows clear Coulomb friction, which adds damping, but does not alter the local stiffness characteristics. The fact that the slopes of the curves in the two areas differ more at the master side than at the environment, shows how the stiffness difference between the two areas is 'blown up'. In fact, the difference is such that the areas easily can be distinguished. This enhancement of discriminability between tissues could enable surgeons to more securely define tumor boundaries, and have a higher confidence on whether crucial structures in the neighborhood are clean or in an infected zone. And, as surgeons are able to feel better, safety will increase.

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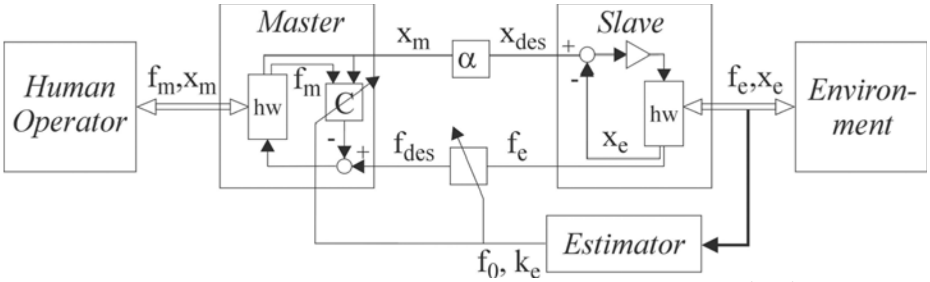

*Figure 2. Experimental results on the interaction with a rubber band: the environment (grey), and the positions and forces at the interface to the human operator (black). The slope of the position-force curves denotes the local stiffness.*

## Robotic rehabilitation over the internet

*Continued from page 3.*

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# Enhanced haptic sensitivity in surgical telemanipulation

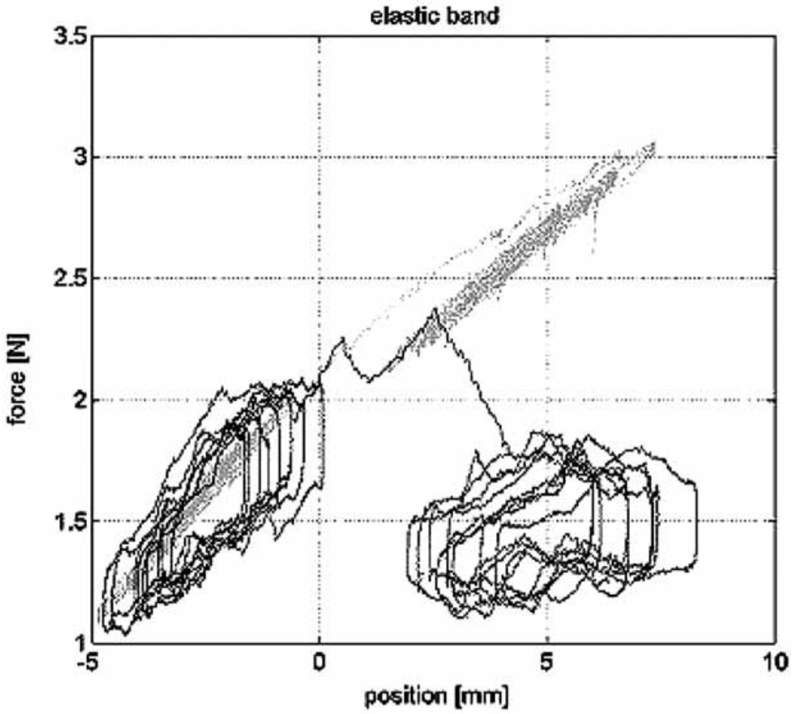

*Figure 1. Block schematic for a one-dimensional teleoperation system with enhanced haptic sensitivity. The slave is under position control, and follows the master, with a motion-scaling factor $\alpha$ if desired. At the haptic interface, adaptive impedance control is implemented, using information about the environment stiffness $k_e$ and an offset force $f_0$ obtained by real-time estimation.*

Robot-assisted minimally-invasive surgery is a recent driving field for research on haptic feedback within telemanipulation. In minimally-invasive surgery (MIS), long-shafted robot tools are inserted into the patient through small incisions, thereby reducing trauma and recovery time. The use of a robot helps the surgeon to overcome traditional MIS drawbacks such as reduced dexterity and the non-trivial hand-eye coordination problem. In bilateral telemanipulation, the human operator manipulates a haptic interface through which the movements of the surgical robot holding the tools can be controlled. The interface offers the operator visual and haptic information about the remote surgical scene.

Traditionally, the performance of a telemanipulation system is judged by its stability, its tracking behavior, and the obtained transparency. In addition to these system capabilities, we are interested in enhancing the haptic perceptual capabilities of the surgeon through the medical telerobot. This would allow the surgeon to better discriminate between tissues than by bare hand or direct manipulation.

### Absolute and relative sensitivity

The benefits of scaled telemanipulation for surgical applications are clear. The robot can extend human capabilities by allowing greater spatial resolution in microsurgical tasks, reducing tremor, and significantly increasing pick and place accuracy.[1] A study by Salcudean et al.[2] shows that using scaled-force feedback yields better force-tracking behavior combined with significantly less fatigue and a higher confidence level.

Scaling techniques allow absolute human thresholds to be overcome: smaller forces can be perceived than with the bare hand, and micrometer-scale motions can be performed accurately. However, humans also have differential thresholds. Even within the range where the human proprioceptive system is very sensitive, a certain difference in stimuli needs to be present in order for the human to be able to distinguish between the two.

Within surgical procedures, surgeons specifically use their haptic senses to decide on a variety of problems. An artery or vein that is hidden beneath fat e.g., can be located by probing the tissue because the vein or artery denotes a stiffer object embedded in the soft fat. Also to define the boundaries of e.g. tumorous tissue within healthy tissue, stiffness discrimination is most important.

These examples, given by experienced surgeons, all can be related to one requirement for a telesurgical system: the human operator should be able to discriminate between the stiffness of different (soft) tissues as well as within open surgery.

According to Weber, stiffness discrimination follows a relative law.[3] Only a slight difference is necessary for differentiating soft tissues, while more stiff objects need to differ by a much greater amount in order to be distinguishable by a human. This relative law suggests that, in order to ameliorate discriminative abilities through the system by a factor $\sigma$, environment stiffness $k_e$ should be transmitted to the operator in an exponential relationship: $k_t = K k_e^{\sigma}$, with K being a constant scaling factor. Naturally, this exponential relationship cannot be obtained by using standard linear techniques.

### Telemanipulation control for enhanced sensitivity

An extended Kalman filter estimates the encountered stiffness in real time. The control gains of the impedance controller of the haptic interface are adapted to the online estimation of the environment stiffness (see Figure 1). Mathematical manipulation allows for the

*Continues on page 10.*

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